Project Kick-off Meeting

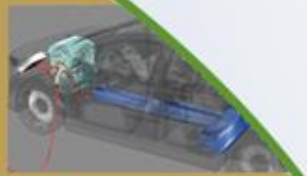
Advanced Solid Sorbent CO_2 Capture

Bench-scale Development of an Advanced Solid Sorbent-based CO_2 Capture Process for Coal-fired Power Plants

Project # DE-FE0007707

RTI International: Thomas Nelson, Luke Coleman, Jian-Ping Shen, Raghubir Gupta
Pennsylvania State University: Chunshan Song, Xiaoxing Wang
DOE Project Manager: Bruce Lani

Pittsburgh, PA - December 14th, 2011



Presentation Overview

- Project Overview
- Project Background
- Technical Approach
- Project Objectives
- Project Team
- Project Structure
- Project Approach and Milestones

Project Overview

FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy

National Energy Technology Laboratory

Bench-Scale and Slipstream Development and Testing of Post-Combustion Carbon Dioxide Capture and Separation Technology for Application to Existing Coal-Fired Power Plants

Funding Opportunity Number: DE-FOA-0000403

Announcement Type: Initial

CFDA Number: 81.089 Fossil Energy Research and Development

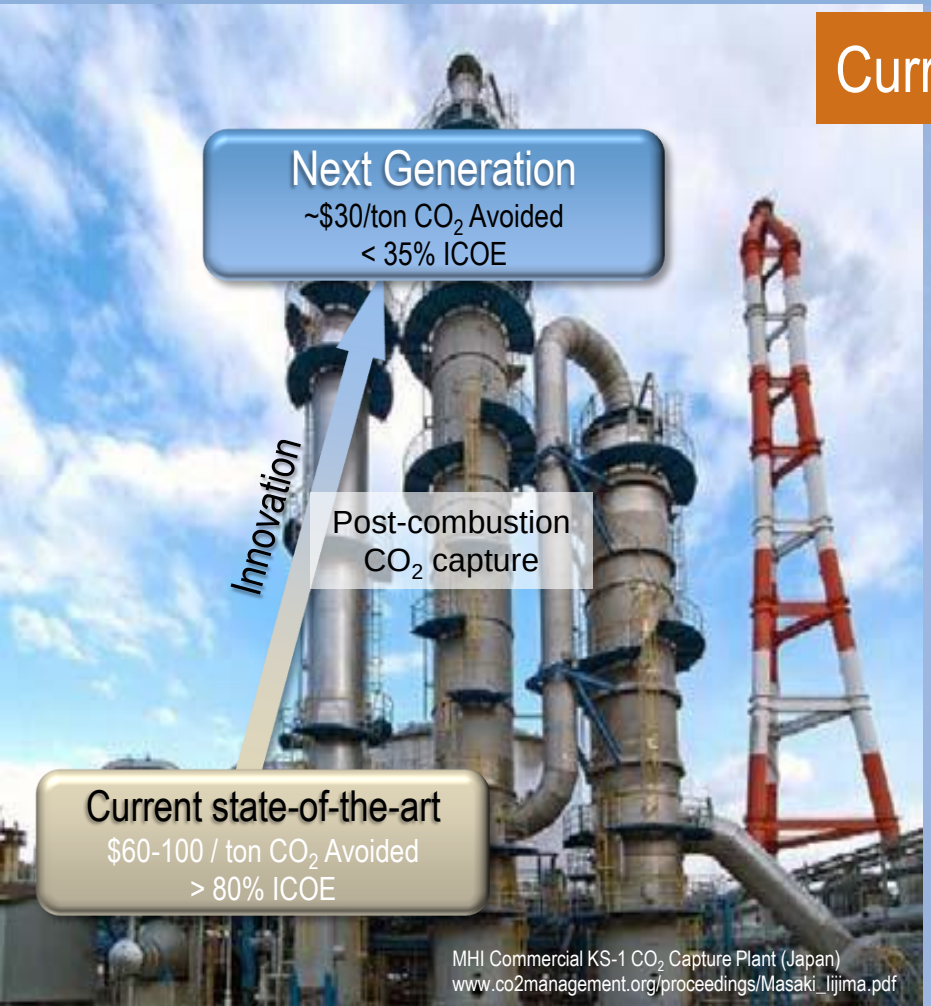
FOA Issue Date:	**1/31/2011**
Letter of Intent Due Date:	**Not Applicable**
Pre-Application Due Date:	**Not Applicable**
Application Due Date:	**3/23/2011 at 8:00 PM Eastern Time**

This Announcement will remain open until the Application Due Date indicated above

Project Overview

- Project # DE-FE0007707
- Total project value: $3,847,161
  - DOE Share: $2,997,038 (77.8%)
  - Cost Share: $850,123 (22.2%)
- Period of Performance: 10/1/2011 to 9/30/2014 (36 mos)
- Project Team (major project partners):
  - RTI International
  - Pennsylvania State University
  - Masdar
- **Objective:** evaluate and demonstrate the potential of an advanced, solid sorbent CO_2 capture process to achieve DOE's CO_2 capture performance targets of >90% CO_2 capture with <35% increase in cost of electricity

Project Background



MHI Commercial KS-1 CO_2 Capture Plant (Japan)
www.co2management.org/proceedings/Masaki_Iijima.pdf

Current SOTA technology – Driver for R&D

High thermal and electrical energy requirements

- Large quantity of high quality steam required for solvent regeneration → derates low-pressure steam turbine
- Large compression energy requirement due to low CO_2 partial pressure generated during solvent regeneration → derates power
- Parasitic power load ranges from 1,200 to 1,500 kJ_e / kg CO_2

High capital and operating costs

- Extremely large process equipment
- Expensive materials of construction
- High degradation rates due to O_2 and SO_2 in flue gas
- Evaporative losses and wastewater treatment requirements

Result

- Increase in Cost of Electricity (ICOE): > 65%
- Cost of CO_2 Avoided: > $60 / tonne

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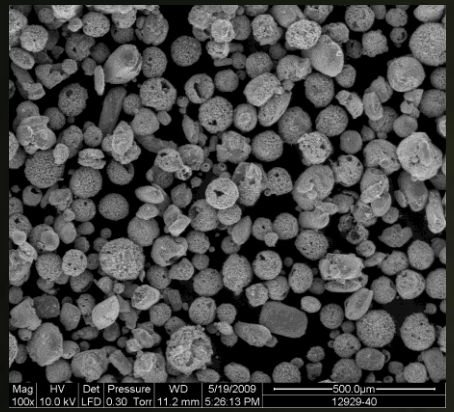
Solid Sorbent CO_2 Capture

RTI solid CO_2 capture sorbents



Solid Sorbent technologies are being developed as general replacements for amine-based CO_2 capture as well as for niche applications that can leverage specific advantages of these technologies.

- **Advantages**
  - Reduced sensible heat load due to lower heat capacities
  - Lower heats of absorption
  - Higher CO_2 working capacity potential
    - Higher active species concentration
    - Higher active species utilization
  - Lower separation / regeneration energy potential
  - Avoids evaporative losses associated with solvent systems
  - Lower cost potential of many bulk sorbent
- **Challenges**
  - Heat transfer, heat integration and water management
  - Solids handling (Fluidized-bed) and Gas switching (Fixed-bed)
  - Physical strength (attrition, crush strength)
  - Pressure drop
  - Separation / Regeneration energy requirement

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R&D Opportunity

Path to Reducing ICOE and Cost of CO_2 Avoided

ICOE Breakdown for SOTA CO_2 Capture Process[1] = 56% Power Consumption + 33% Capital Expense + 11% Operating Expense

Breakdown of the Thermal Regeneration Energy Load

$$q_R = \left[\frac{C_P(T_R - T_F)}{\Delta\alpha} \cdot \frac{M_{sol}}{M_{CO_2}} \cdot \frac{1}{x_{sol}}\right] + \left[\Delta H_{V,H_2O} \cdot \frac{p_{H_2O}}{p_{CO_2}} \cdot \frac{1}{M_{CO_2}}\right] + \left[\frac{\Delta H_{abs,CO_2}}{M_{CO_2}}\right]$$

Sensible Heat — Heat of Vaporization — Heat of Absorption

Solvent	C_p [J/g K]	Δh_{abs} [kJ/mol]	Δh_{vap} [kJ/mol]	X_{solv} [mol active species / mol material]	$\Delta\alpha$ [mol CO_2/ mol material]	Thermal Regeneration Energy Load [GJ/tonne CO_2]
MEA (30%wt)	3.8	85	40	0.11	0.34	3.22
Lower Energy Sorbent System	↓	↓	0	↑	↑	↓

[1] Rochelle, G. T. Amine Scrubbing for CO_2 Capture. *Science* **2009,** 325, 1652-1654.

Project Background

Process Technology

Fluidized Moving-Bed Reactor Process Concept

FMBR design shows most potential to leverage the benefits associated with fluidized-bed reactors:

- Process intensification by minimizing number of process vessels and sorbent load
- Minimizes total thermal regeneration energy by enabling the use of solid sorbents with high CO_2 loadings and eliminates thermal cycling of process equipment
- Provides superior gas-solid heat and mass transfer characteristics
- Effectively manages heat loads in both the CO_2 Adsorber and Sorbent Regenerator,
- Utilizes equipment that are commercially available at the scale required.

Fluidized Moving-bed Reactor Development

Detailed process engineering of viable process configurations

- Effective heat management in both the CO_2 Adsorber and Sorbent Regenerator is essential for optimal performance (dominant resistance)
- Most promising design: circulating, fluidized, moving-bed reactor (FMBR) process design

Feasibility testing of FMBR process design

Fluidized, Moving-bed Reactor Studies

Hydrodynamics

- Bench-scale hydrodynamic testing using “Cold Flow” systems
- Bench-scale data collection for prototype system design
- Solids handling and control of fluidized, moving-bed reactors
- Computational fluid dynamics modeling

Heat Transfer and Heat Management

- Fluidized and moving, fluidized-bed reactor systems
- Bench-scale heat transfer testing
- Novel heat integration simulation and modeling

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Project Background

Sorbent Technology

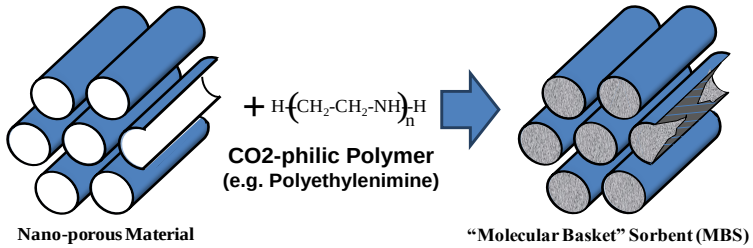
Advanced Solid Sorbents for CO_2 Capture

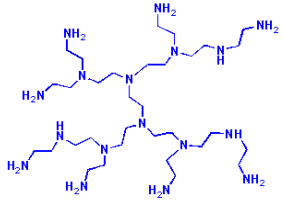
To realize the benefits of a circulating FMBR process design, a suitable CO_2 sorbent must:

- Achieve dynamic CO_2 loadings >10 wt% under flue gas conditions
- Exhibit a heat of CO_2 adsorption of <80 kJ/mol of CO_2
- Be a fluidizable and attrition resistant material
- Be inexpensive (preferably < $10/kg)

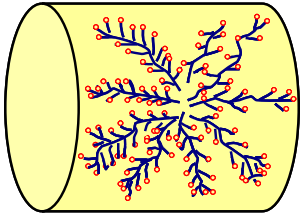
Impregnated amine sorbents have potential to meet these targets

Selection of Solid Sorbent





Polyethylenimine (PEI)



Immobilize PEI into Nano-Pore

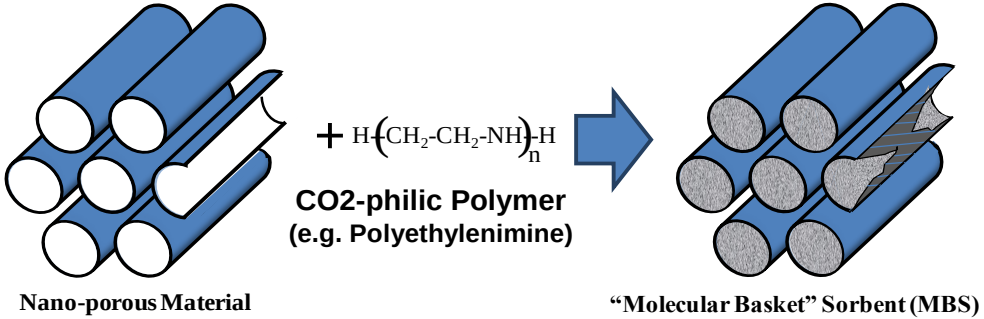
Impregnation of PEI in the pore structure of a high surface area support

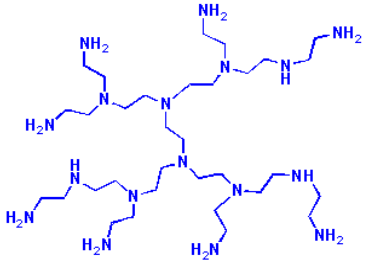
Impregnated Amine Sorbents

- Prepared by simple wet impregnation technique in which a nitrogenous base (primary or secondary amine) is dissolved in a solvent, intimately mixed with a support material, and heated to evaporate the solvent leaving a well-dispersed nitrogenous base in the support pore structure
- Polymeric amines have a high density of multiple CO_2 absorbing site types: primary, secondary, and tertiary sites
- Impregnated-amine sorbents are attractive for the following reasons:
  - higher amine loadings which translates to higher CO_2 loading capacities (14-20 wt% CO_2)
  - can utilize polymeric amines (e.g. polyethyleneimine) with high amine/C ratios and high CO_2 loading potential without performing complicated in-pore polymerization reactions
  - can utilize low cost support materials – there is no requirement that support surface have a high density of surface –OH groups
  - can utilize low cost nitrogenous bases instead of aminosilicates.

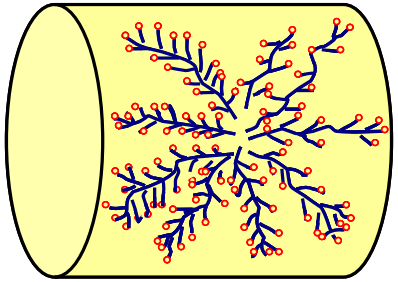
PSU's MBS CO_2 Adsorbing Material

"Molecular Basket Sorbent" (MBS)





Polyethylenimine (PEI)



Immobilize PEI into Nano-Pore

PSU's Molecular Basket Sorbent (MBS) material is one of the most promising impregnated amine sorbents:

- High CO_2 loadings (>14 wt% CO_2)
- High CO_2/N_2 selectivity (> 1000)
- Reasonable heat of adsorption (*66 kJ/mol*)
- Can be prepared from inexpensive high surface area materials and maintain performance
- Utilizes CO_2-philic polymer, polyethyleneimine (PEI)

Over 10 years of focused R&D with a vast amount of published data

PSU provided RTI with a sample of the MBS material for performance evaluation

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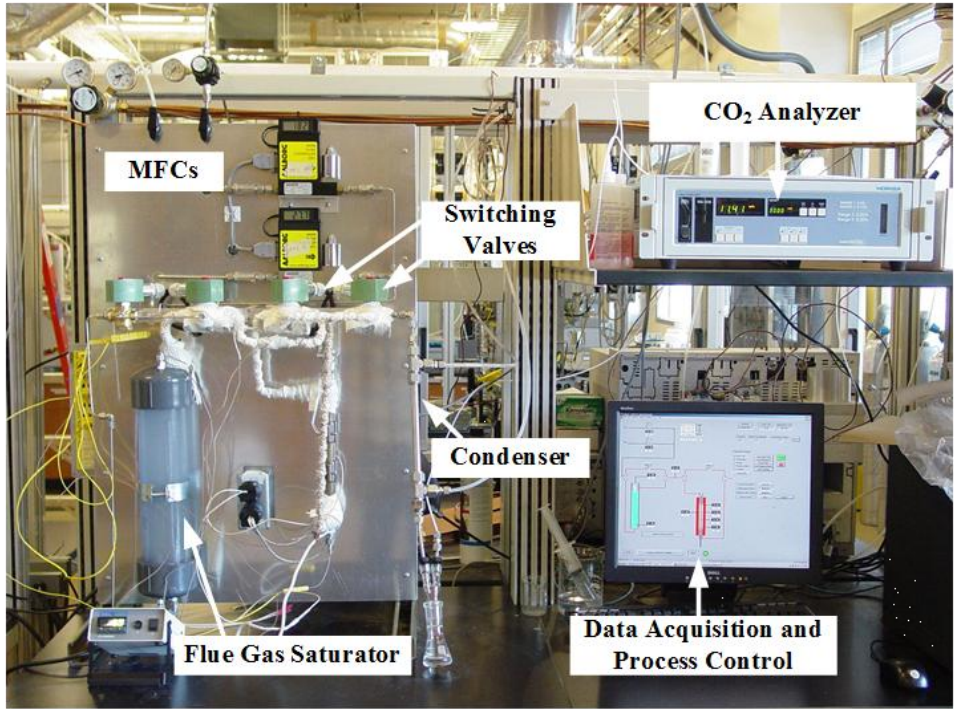
RTI's Lab-scale Automated PBR System



RTI's Fully Automated, Packed-Bed Reactor System for Multi-cycle CO_2 Capture-Regeneration Testing

Capabilities

- Fully-automated operation
- Fully-automated data analysis and report generation
- Multi-cycle, absorption-regeneration experiments
- Rapid sorbent screening experiments
- Comprehensive parametric evaluation
  - Window of operation
  - Kinetic studies
- Sorbent stability experiment (multi-cycle)
- Long-term effect of contaminants

Measurables

- Dynamic CO_2 loading capacity
- Rate of CO_2 loading on sorbent (wt%/min)
- Removal of CO_2 from flue gas
- Thermal waves due to absorption or desorption
- Pressure drop across packed bed

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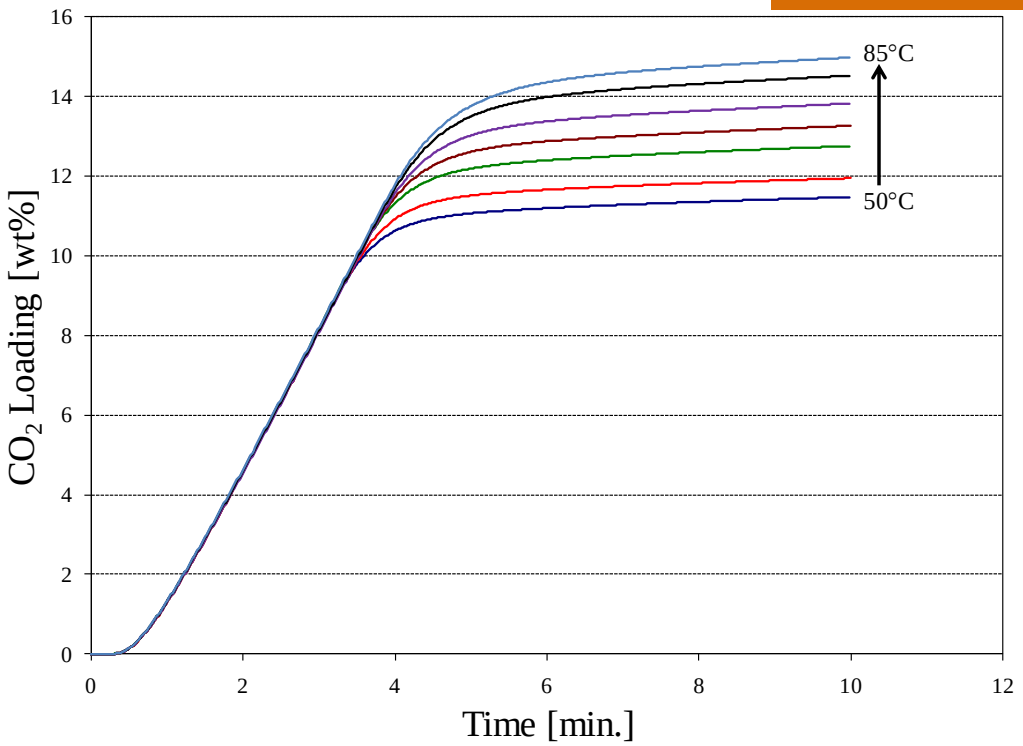
Effect of Adsorption Temperature



Very intriguing performance characteristics which could have very positive implications on the performance of the process

- Test Conditions
  - Gas Composition: 15 %vol CO_2/N_2
  - Total Pressure: 1 bar
  - Temperature Range: 50 to 85°C
  - GHSV = 2,250 h^{-1}
- Results and Observations
  - CO_2 loading increased from 11.5 to 15 wt% CO_2 with increasing adsorption temperature
  - Very unique relationship between CO_2 loading and temperature
  - Typically loading and rate of loading decrease with increasing temperature
    - CO_2 adsorption is an exothermic reaction that is thermodynamically favored at lower temperatures

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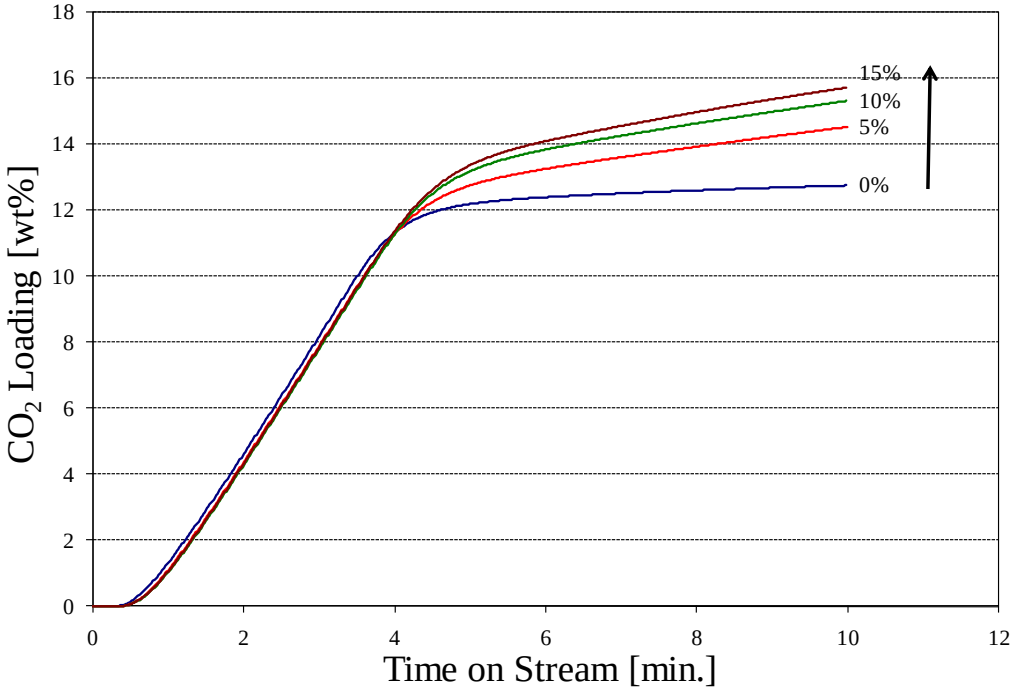
Effect of H_2O Concentration



H_2O is beneficial to CO_2 loading but may be detrimental to CO_2 product quality and regeneration energy

- Test Conditions
  - Gas Composition:
    - 15 %vol CO_2/ (0 to 15 %vol H_2O) / N_2
  - Total Pressure: 1 bar
  - Temperature Range: 65°C
  - GHSV = 2,250 h^{-1}
- Results and Observations
  - Water has a beneficial effect on CO_2 loading
  - Intriguing observation as H_2O general has a negative effect on many other CO_2 adsorbent materials (e.g., zeolites; MOFs)
  - PSU recently demonstrated that water interacts with the sorbent to form bicarbonates
    - Much slower kinetics
    - Requires higher temperature regeneration
    - Reduced CO_2 product purity

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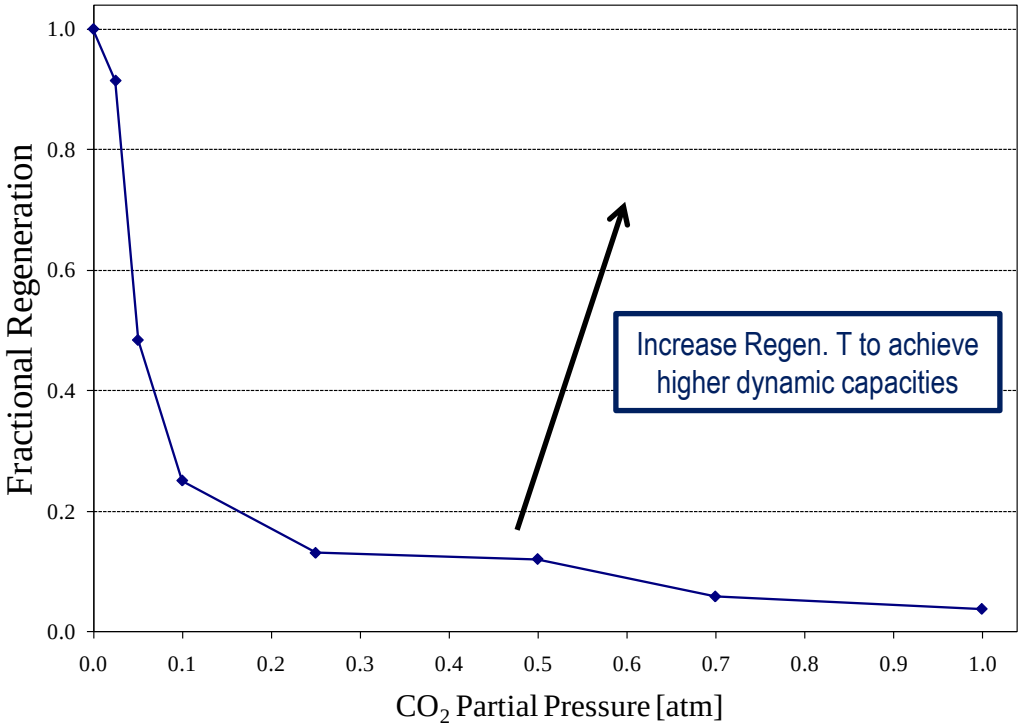
Regeneration in the Presence of CO_2 @ 90°C



Low working capacities if regenerated at 90°C in presence of CO_2
Increased regen. temperatures are necessary

- Test Conditions

Adsorption
- Gas Composition:15 %vol CO_2/15%vol H_2O/N_2
- Temperature: 65°C

Regeneration
- Gas Composition:
  - CO_2/N_2 blends ranging 1 bar N_2 to 1 bar CO_2
- Total Pressure: 1 bar
- Temperature: 90°C

- Results and Observations
  - MBS regenerability is strongly affected by presence of CO_2 in the regen. gas
  - Effectively decreases the sorbent's working capacity
  - Significant vacuum or steam-purge will be required
    - Energy and cost intensive

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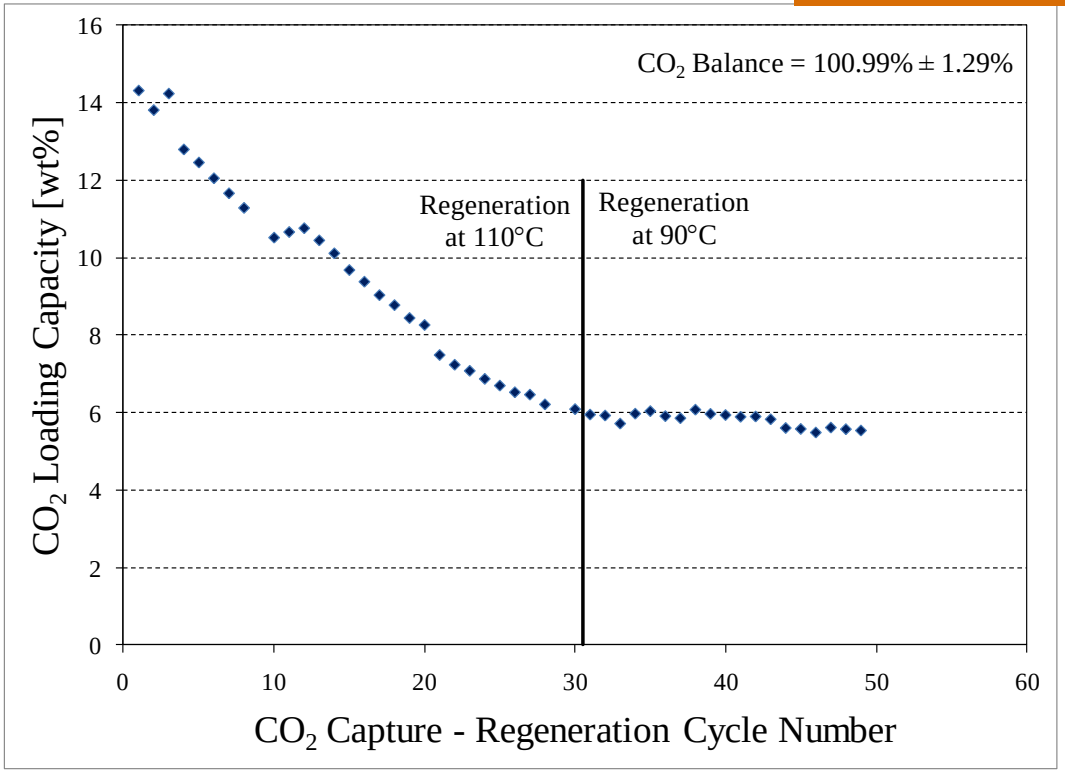
Thermal Stability / Degradation



Increased regeneration temperatures are necessary to realize high dynamic capacities

- Test Conditions

  Adsorption
  - Gas Composition:15 %vol CO_2/15%vol H_2O/N_2
  - Temperature: 65°C

  Regeneration
  - Gas Composition: 1 bar N_2
  - Temperature: 110°C → 90°C

- Results and Observations
  - MBS provided to RTI experienced rapid degradation when regenerated at 110°C
    - >50% decrease in CO_2 loading after 30 cycles
    - GC-MS analysis of condensate indicated that the active agent, PEI, was thermally decomposing
  - Reducing regen. T to 90°C led to a stabilization on sorbent performance
  - PSU continues to make progress in improving the thermal stability of their MBS materials

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Technical Approach

Project Objectives

Project Objectives

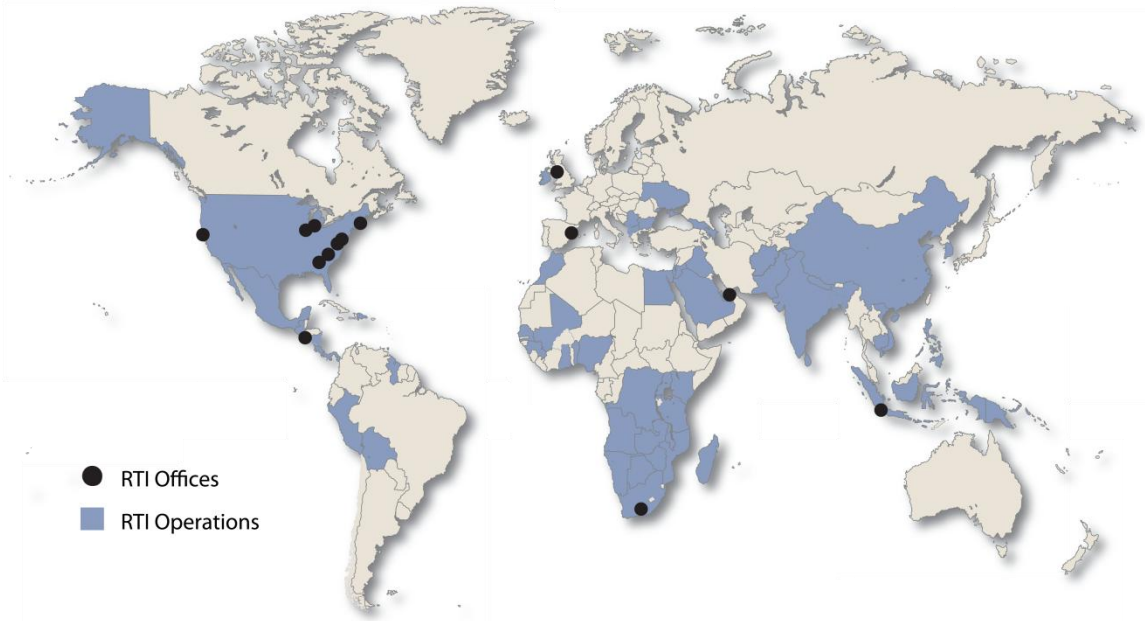
Budget Period 1	Budget Period 2	Budget Period 3
10/1/2011 to 9/30/2012	10/1/2012 to 7/31/2013	8/1/2013 to 9/30/2014
• Improve the stability of base PEI reactant to further improve critical CO_2 capture and regeneration performance parameters • Transition PSU's fixed-bed MBS materials into fluidizable form • Determine how critical process elements influence reactor temperature profiles, heat and mass transfer rates, and solids flow dynamics • Develop commercial projections for MBS-based process design and cost and performance baselines	• Produce an advanced MBS material exhibiting significant improvements in critical properties as compared to sorbents produced in Budget Period 1. • Utilize critical process engineering data collected with a laboratory CO_2 capture contactor to design a bench-scale CO_2 capture prototype based on the advanced, fluidized-bed MBS material.	• Utilize pilot manufacturing equipment to scale-up production of the fluidized-bed MBS material to 1,000 lbs • Demonstrate, on a bench-scale, effective and continuous CO_2 capture from natural gas- and coal-fired flue gas using a MBS-based process system able to remove CO_2 to meet targets set by the research program. • Substantially prove the technical and economic competitiveness of a commercial embodiment of the MBS-based CO_2 capture process through detailed techno-economic and environmental analyses.

Project Team

Project Team

Team Member	Project Role
RTI International	• Prime Recipient; project management • Process development; CO_2 process design, heat integration • Sorbent development; expertise in fluidized-bed sorbents
PSU	• PSU's Energy Institute • Sorbent development/improvement of base reactive agent • Sorbent preparation and testing facilities
Masdar	• Technology evaluation; process engineering support • Parallel R&D efforts to evaluate technology for NG application • Bench-scale and pilot testing support
Süd-Chemie	• Commercial catalyst/sorbent manufacturing company • Sorbent scale-up; commercial manufacturing evaluation • Provider of support materials for evaluation
Foster Wheeler	• Engineering and construction contractor • Technical and economic evaluation; process design support • Fluidized-bed reactor design expertise
UNC-CH	• Host site; UNC-Chapel Hill Energy Services Department • Coal-fired power plant; supports new technology demos

RTI International



- Research budget >$750MM
- 13% average annual growth over the last 10 years.
- One of the worlds leading research organizations:
  - >4,200 professionals in more than 40 countries
  - High-quality scientific staff with tremendous breadth
  - Over 130 different academic disciplines

Mission: To improve the human condition by turning knowledge into practice

RTI's Center for Energy Technology (CET)

RTI's Johnson Science and Engineering Building
Home of the Center for Energy Technology

- CET develops **advanced energy technologies** to address some of the world's great energy challenges

Advanced Gasification
- Syngas cleanup/conditioning
- Substitute natural gas production
- Hydrogen production (Chemical Looping)

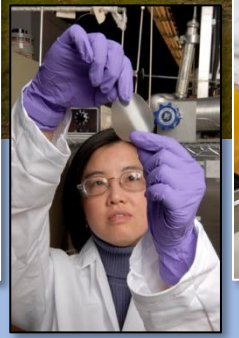
Biomass & Biofuels
- Biomass gasification
- Syngas cleanup/conditioning
- Pyrolysis to biocrude and conventional fuels

Fuels and Chemicals
- Syngas to fuels and chemicals
- Hydrocarbon desulfurization

Carbon Capture & Reuse
- Post-combustion CO_2 capture
- Pre-combustion CO_2 capture
- CO_2 reuse for fuels chemicals

Industrial Water
- Industrial water reuse
- Energy recovery, waste heat utilization

Shale Gas
- Gas separation & processing
- Process water treatment



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Project: 50 MW_e Pre-Commercial Syngas Cleaning

Project Objective: Demonstrate RTI's Warm Syngas Clean-up technology with integrated carbon capture at pre-commercial scale at an operating gasification plant

Project Team		Role
RTI	RTI INTERNATIONAL	Project management; technology developer
Tampa Electric	TECO TAMPA ELECTRIC	Host site and CO_2 sequestration oversight
Shaw Group	Shaw a world of Solutions	Engineering
BASF	BASF The Chemical Company	Provide technology (aMDEA®) for syngas CO_2 capture
Süd-Chemie	SÜD-CHEMIE	Produce RTI-3 desulfurization sorbent & other catalysts
DOE/NETL	NETL	Funding agency; project consultation

Technology: Syngas contaminant removal at elevated temperature and pressure, maintaining high thermal efficiency of gasification process.

- Developed over 10+ years from concept to pre-commercial scale
- R&D 100 Award (2004) for regenerable, desulfurization sorbent

Project Detail: Combined syngas cleanup & CO_2 capture demonstration

- $170M (DOE funding) to design, construct, commission, and operate
- 50 MW_e equivalent scale; sequester 300,000 tons/yr of CO_2
- Impact: Improve cost-effectiveness and efficiency of gasification systems

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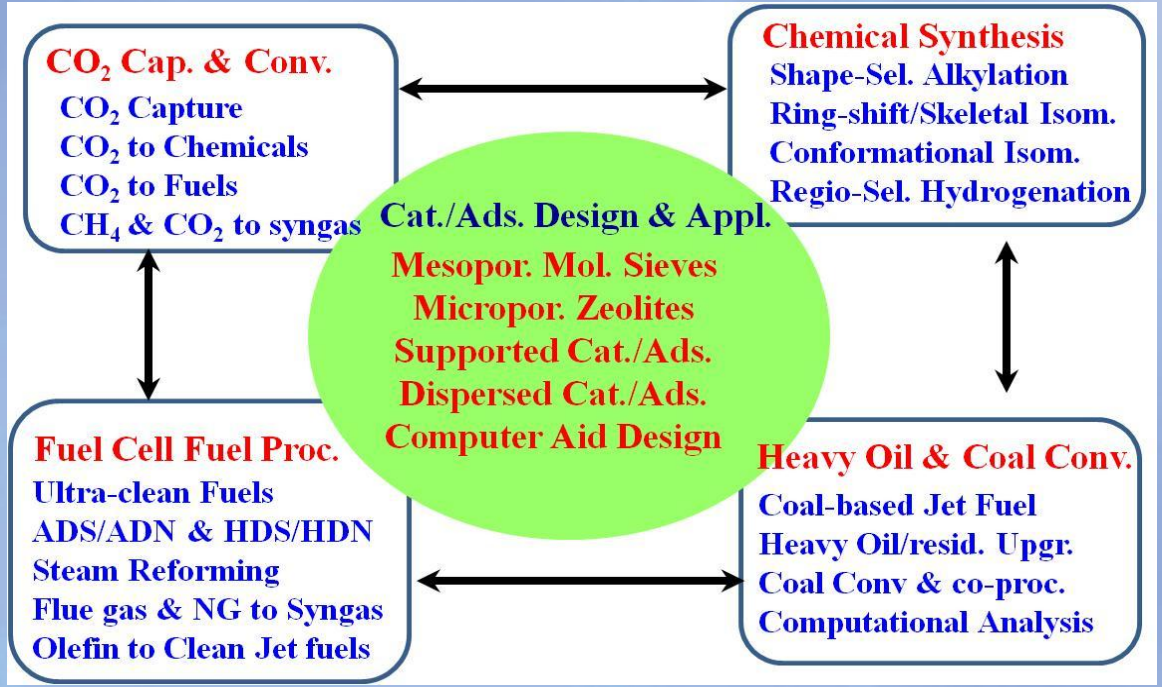
Pennsylvania State University

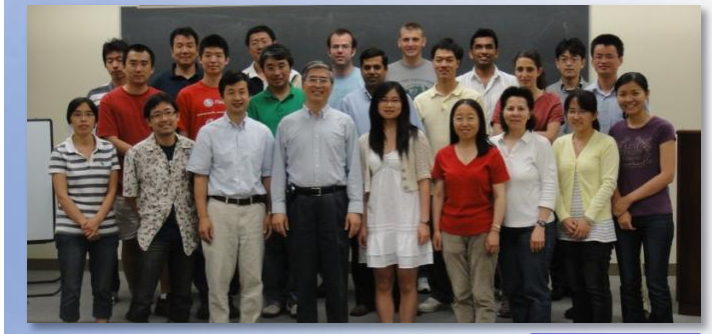
Clean Fuels and Catalysis Research at Penn State



Expertise in Material Development

Research Team:

2 Faculties, 2 staffs, 3 visiting scholars, 5 Post-doc, and 9 Grad Students



http://www.energy.psu.edu/personnel/CSong.html

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Masdar

Established in 2006, Abu Dhabi-based Masdar is a commercially driven enterprise operating through five integrated units to reach the broad boundaries of the renewable energy & sustainable technology industry

Masdar

- Project co-funding partner
- Aims to help drive the development of clean fossil fuel energy technologies
- Masdar Carbon flagship initiative involves the development of a large-scale CCS network in Abu Dhabi
- Masdar Institute is an independent, research-driven graduate university, partnered with MIT
- **Project roles** involves providing engineering expertise to evaluate technical feasibility and potential application to natural gas-fired plants. R&D efforts focused on parallel development of technology for natural gas application

Memorandum of Understanding between Department of Energy & Masdar

- DOE & Masdar signed MoU in 2010 to promote collaboration on clean/sustainable energy technologies
- Cooperation in three key areas: Carbon Capture; & Sequestration Water & Biofuels; Building Technology

Masdar مصدر
A MUBADALA COMPANY

Press Release

Masdar, RTI and US Department of Energy Partner in Revolutionary CCS Research Project

Companies to investigate use of solid sorbent technology in carbon capture and storage

Abu Dhabi-UAE: 23 August, 2011 – Masdar today announced their collaboration with RTI International, an independent non-profit research institute, on a high potential carbon capture technology research project set to revolutionise the carbon capture and storage (CCS) space. The project will examine the use of solid sorbent technology for the capture of carbon dioxide (CO_2) from coal and gas-fired power station flue gases, targeting a significant cost reduction in carbon dioxide capture over the best available technology today.

The US Department of Energy (DoE) and Masdar are co-funding the innovative research in an agreement that sees Masdar provide an additional US$0.7 million in funding to the US Department of Energy's core US$3million budget.

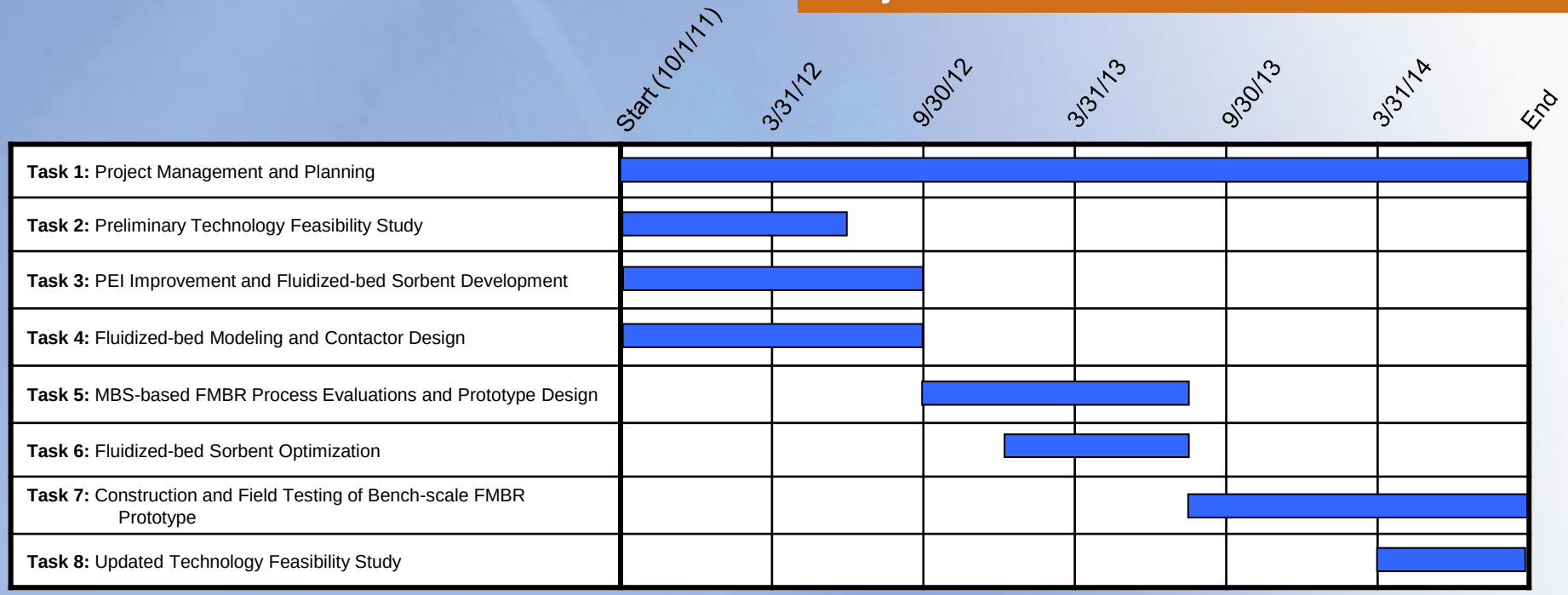
Bader Al Lamki, Associate Director of Masdar Carbon explained, "Masdar Carbon is committed to the innovation and development of clean fossil fuel technologies aimed at reducing carbon dioxide emissions both locally and globally. We are excited to work with RTI International and the US Department of Energy on this innovative project which has the potential to revolutionise both the economics and technology of CCS practices".

In addition to its co-funding with the DoE, Masdar Institute is working with RTI International to extend the research scope into the technology's application for gas fired power station flue gases.

Dr Fred Moavenzade, President of the Masdar Insitute commented: "We at Masdar Institute are very happy to participate in this very important and timely collaborative research project. Our research agenda emphasizes clean energy and

Project Structure and Budget

Project Tasks and Schedule



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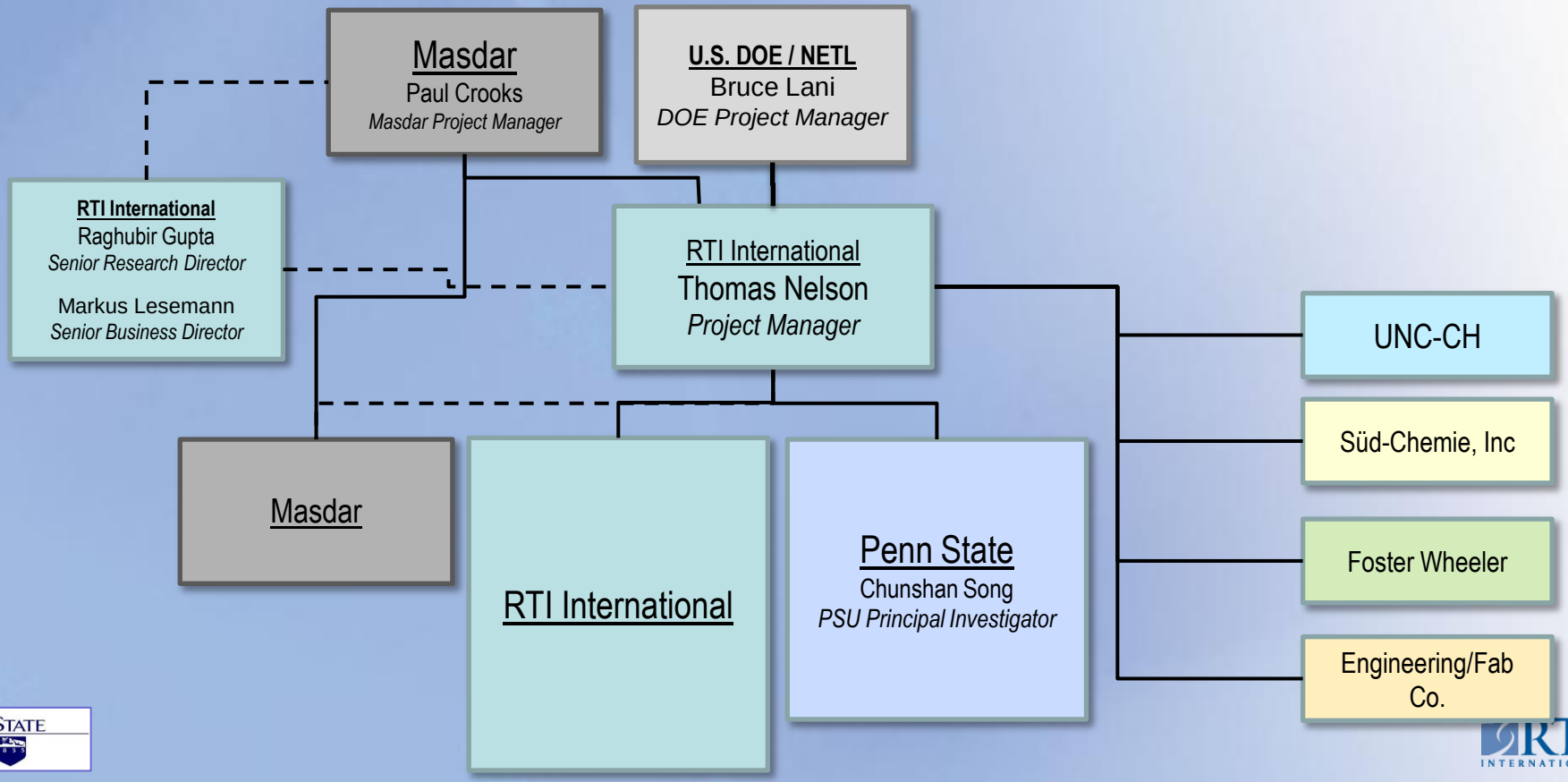
Task 1 - Project Management and Planning



Preliminary Technology Feasibility Study

NATIONAL ENERGY TECHNOLOGY LABORATORY

Cost and Performance Baseline for Fossil Energy Plants
Volume 1: Bituminous Coal and Natural Gas to Electricity
Revision 2, November 2010
DOE/NETL-2010/1397

U.S. DEPARTMENT OF ENERGY

- Goal:
  - *Develop preliminary commercial design, cost, and performance projections for MBS-based CO_2 capture process*
- Deliverables *(*BP1*, Specified in FOA)*:
  - PFDs identifying all major process equipment for the combined CO_2 capture and compression system
  - Complete stream tables showing operating pressures, temperatures, compositions, and enthalpies for all streams
  - Cost estimates for all major process equipment and/or process consumables
  - Parasitic power load; capital and operating cost; levelized cost of electricity
  - Technology performance targets (overall targets and target for each stage of development)
    - e.g., sorbent cost, sorbent make-up rates (stability targets), CO_2 loading
- Current Activities:
  - Preparing initial PFDs and process descriptions
  - Modification of existing Aspen flowsheets
  - Preparation to measure CO_2 loading – CO_2 partial pressure relationship, heat of CO_2 absorption, and specific heat capacity for baseline PEI sorbent

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Aspen Simulation for Baseline Power Plant

- Developed and verified with Case 12 from DOE/NETL-2007/1281
  - Net 550 MW_e power plant; CO_2 captured with Fluor Econamine FG+ process (can be replaced by various capture processes)
- CO_2 capture process is modeled in a separate Aspen sim.; steam load and elec. power consumed are accounted for in this model
- Simulation tool estimates the power plants net electrical energy output
  - Accounts for quality and quantity of steam used
  - Accounts for compression energy – can account for different CO_2 pressures in regenerator off-gas
  - Estimates parasitic power load as both as $kJ_{th}/kgCO_2$ and GJ_e/tonne CO_2

Sorbent Development

- Goal: *Improve the thermal and chemical stability of base PEI reactant while transitioning fixed-bed MBS material into a fluidizable form*
- Deliverables (BP1):
  - Sorbent with improved PEI stability compared to baseline, fixed-bed MBS material
  - Fluidizable PEI-based sorbent with performance properties similar to fixed-bed sorbent
  - 15kg of fluidized-bed sorbent along with scale-up preparation procedure
- PSU Activities:
  - Strengthening of PEI and support material chemical bond
  - Evaluating PEIs of various molecular weights
  - Evaluating PEIs of various degrees of polymer branching
- RTI Activities:
  - Evaluating inexpensive support materials
  - Evaluating fluidized-bed production techniques for MBS materials
  - Assisting base PEI improvement activities

Characteristics of Suitable Support Materials	
Particle diameter	50 to 200 μm
Bulk (packed) density	0.7 to 1.5 g/cm^3
Surface area	> 50 m^2/g
Attrition index	< 20* (Davison Index)
Sorbent Cost	< $10/kg

CO_2 Capture Research Facilities at PSU

Fixed-bed testing system

TGA-DSC

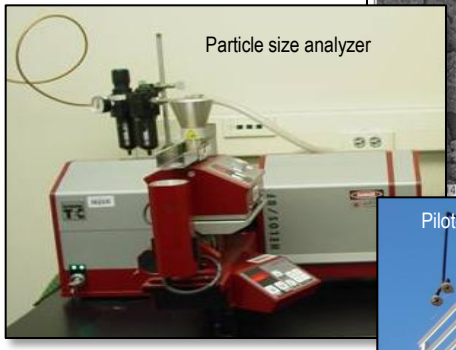
in situ DRIFTS/FTIR

ASAP 2020

PENNSTATE
1855

Sorbent Development Capabilities at RTI

SEM of RTI-developed Sorbent


Particle size analyzer

Pilot-Scale NIRO Mobile Minor spray dryer

Pilot-scale Attrition Test System

CET's Bonnet Lab-scale, High-Torque Extruder

RTI-developed catalysts and sorbents

- Laboratories for processing gram to kilogram quantities of materials
- Spray drying and extrusion capabilities
- Multiple fluidized-bed and fixed-bed reactor testing systems
- Physical and chemical characterization
  - Surface area
  - Pore size analysis
  - Particle size distribution
  - Attrition-resistance
  - Adsorption/desorption testing
  - Phase transition analysis
  - Elemental analysis

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Process Development

- Goal: *Determine the influence that specific process elements and sorbent properties have on reactor temperature profiles, CO_2 capture performance, and heat and mass transfer rates*
- Deliverables (BP1):
  - Flexible CFD model of a FMBR that can be used to evaluate the influence of reactor geometry, sorbent physical properties, and process operating conditions on the performance of the CO_2 Absorber / Sorbent Regenerator
  - Design insights for the single-stage contactor and commercial system to support the Task 2 and Subtask 4.2
- Current Activities:
  - Initial work to develop a basic hydrodynamic model of a moving, fluidized-bed reactor

RTI's CUP Facility – Natural Gas Testing

RTI CUP Facility Specifications

- ~ 5 MW_t boiler – Natural Gas-fired
- 13,800 lbs/hr steam production
- Flue Gas composition:
  - 7.4 vol% CO_2
  - 7.7 vol% O_2
  - CO = 70ppm; NO = 35ppm
- Flue Gas temperature: 165°C
- CO_2 produced: ~ 25 TPD
- Field Testing: utilize cooling water, FG exhaust, steam

UNC-CH – Coal Power Plant Host Site

University of North Carolina – Chapel Hill Co-Generation Power Plant

- UNC Chapel Hill Co-Generation Facility
  - Generates steam and electricity
  - Electric Capacity: 28 MW_e
  - Heating Capacity: 900,000 lbs/hr
  - 2 coal-fired ACFBs (55% of HC); 2 oil/gas boilers (45% of HC)
  - Coal Feed: ~ 50,000 lbs/hr
  - CO_2 Produced: 1500 tons/day

Project Milestones – BP1

Task	Milestone Description	Planned Completion	Verification Method
1	**A.** Updated Project Management Plan	10/15/2011	Project Management Plan file
1	**B.** Kick-off Meeting	12/14/2011	Presentation file
3.3	**C.** Successful scale-up of fluidized-bed MBS material	5/31/2012	Quarterly Report #3; 30 lbs of sorbent available
2.0	**D.** Favorable technology feasibility study	6/30/2012	Topical report describing technology study methods & results
4.1	**E.** Working multi-physics, CFD model of FMBR design	6/30/2012	Quarterly Report #3
4.2	**F.** Fabrication-ready design and schedule for single-stage FMBR unit	9/30/2012	Engineering Design Package

Technology Development Plan

	Previous Work			Current Project			Future Development		
Yr	< 2011			2011-14			2014 - 16	2016-19	2020+
TRL	1	2	3	4	5	6	7	8	9

Commercial

Proof-of-Concept Feasibility Studies

Laboratory Validation

- Comprehensive sorbent screening and sorbent optimization
- CO_2 capture testing in laboratory reactors with simulated flue gas
- Process modeling

Relevant Environment Validation

- Bench-scale testing of single-stage contactor operating in CO_2 capture and sorbent regeneration modes
- Prototype system shakedown testing at natural gas-fired facility

Prototype Testing

- Prototype system long-term testing at coal-fired UNC power plant (~ 1 ton/day CO_2 capture)

Pilot Validation

- 5 MW (eq) pilot-scale testing at large-scale coal-fired utility plant
- > 100 ton/day CO_2 capture

Demonstration

- 50 -100 MW (eq) pre-commercial scale testing

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Discussion